The Social Costs of Climate Change: The IPCC Second Assessment Report and Beyond

Fankhauser, S.; Tol, R.S.J.

published in
Mitigation and Adaptation Strategies for Global Change
1997

DOI (link to publisher)
10.1023/b:miti.0000027387.05917.ae

document version
Publisher's PDF, also known as Version of record

THE SOCIAL COSTS OF CLIMATE CHANGE: THE IPCC SECOND ASSESSMENT REPORT AND BEYOND

S. FANKHAUSER* and R.S.J.TOL
Institute for Environmental St., De Boelelaan 1115, 1081 HV, Amsterdam, The Netherlands

(Received 23 August 1996; accepted in final form 2 December 1996

Abstract. Climate change is expected to have far-reaching impacts. Earlier studies have estimated an aggregated monetised damage equivalent to 1.5 to 2.0 % of World GDP (for $2 \times CO_2$). According to these estimates, the OECD would face losses equivalent to 1.0 to 1.5 % of GDP, and developing countries 2.0 to 9.0 %. While these figures are preliminary and highly uncertain, recent findings have not, as yet, changed the general picture. As is shown in this paper, estimates that are fully corrected for differences in purchasing power parity do not significantly differ from the initial figures. Newer studies increasingly emphasise adaptation, variability, extreme events, other (non-climate change) stress factors, and the need for integrated assessment of damages. Incorporating these factors has lead to increased differences in estimated impacts between different regions and sectors. Estimates of market impacts in developed countries tended to fall, while non-market impacts have become more important. Marginal damages are more interesting from a policy point of view. Earlier estimates range from about \$5 to \$125 per tonne of carbon, with most estimates at the lower end of this range. These figures are based on power functions in the level of climate change. The rate of change may be equally important, as are the speed of adaptation, restoration and value adjustment. Furthermore, future vulnerability to climate change will differ from current vulnerability: market impacts could fall (relatively) with economic growth while non-market impacts may rise.

Key words: Climate change damage costs

1. Introduction

Knowledge on the impacts of climate change is one of the key factors for an informed policy response. Such knowledge can be presented in many different ways. One way is to express all impacts in a single metric, such as money. Using a monetary metric is an obvious choice for reasons of convenience, but also because it facilitates the comparison of damage costs with the costs of emission reduction. Working Group II of the Intergovernmental Panel on Climate Change (IPCC) has extensively reviewed the physical impacts of climate change on human society and natural ecosystems (Tegart *et al.*, 1990; Tegart and Sheldon, 1992; Watson *et al.*, 1996). This paper reviews available monetary damage assessments, starting from the work of Chapter 6 of IPCC Working Group III (Pearce *et al.*, 1996; cf. also Fankhauser 1994b, 1995a, and Tol, 1995), but adding more recent evidence and developments.

* Samuel Fankhauser is with the Program for Measuring Incremental Costs for the Environment (PRINCE), Global Environment Facility Secretariat, 1818 H Street NW, Washington DC 20433 USA. The views expressed in the paper are his own and not necessarily those of the Global Environment Facility or its associated agencies. Richard S. J. Tol is with the Institute for Environmental Studies, Vrije Universiteit, De Boelelaan 1115, 1081 HV Amsterdam, The Netherlands.

Mitigation and Adaptation Strategies for Global Change **1:** 385–403, 1997.

Information on the impacts of global warming is now available for several regions and countries (Pearce *et al.*, 1996; Watson *et al.*, 1996). The best studied regions are developed countries, in particular the United States, where climate change impacts have been analysed in a series of studies, following initial work by Smith and Tirpak (1989). Other OECD regional studies include CRU/ERL (1992) for the European Union; Parry and Duncan (1995) for the United Kingdom; Kuoppomaeki (1996) for Finland; and Nishioka *et al.* (1995) for Japan. In the context of an Asian Development Bank (ADB, 1994) project on climate change in Asia, global warming impacts have also been analysed for a number of Asian countries (cf. also SAARC, 1992).

Further information on the vulnerability to climate change is increasingly becoming available as countries prepare their first national communication to the Climate Convention. A series of country studies have been, and are being, undertaken in this context. First results are reported in Dixon *et al.* (1996), Lenhart *et al.* (1996) and Smith *et al.* (1996). The global study of Stzrepek and Smith (1995) contains case studies for Africa, Latin America and Asia. Note that, like most damage studies, these assessments are not comprehensive with regard to the range of impacts covered, and that no monetized evaluations are usually undertaken.

Estimates generally combine the costs of adaptation (such as sea level rise protection) and the costs of residual damages (such as the inundation of unprotected areas). However, the assumed level of adaptation is usually arbitrarily chosen, and the process of how adaptation takes place is not spelled out. Exceptions include studies using (variants of) the hedonic approach (e.g., Mendelsohn *et al.*, 1994; Darwin *et al.*, 1995), a technique that assumes full adaptation but can only be used to compare two equilibrium situations. For sea level rise, the trade-off between protection and land loss is sometimes based on optimization calculus (Fankhauser, 1995b; Yohe *et al.*, 1995, 1996).

By far the best studied impact categories are agricultural impacts (cf. Reilly *et al.*, 1996, for an overview) and the costs of sea level rise (cf. Bijlsma *et al.*, 1996). Other impact categories have been studied at a more rudimentary level, while some have hardly exceeded the back of the envelope stage. In addition, several types of impacts have largely been ignored so far, because they could not be sufficiently quantified. Prime examples include famines and vector-borne diseases. In both cases, non- climatic influences are dominant and complex.

Attempts at a comprehensive monetary quantification of all impacts are relatively rare, and usually restricted to the United States (Cline, 1992a; Nordhaus, 1991; Titus, 1992). Preliminary global estimates are found in Fankhauser (1995a) and Tol (1995). Comprehensive studies all take what may be called an enumerative approach, i.e., the impacts of climate change are first listed, then evaluated (monetised), and finally monetary estimates are added up. Possible synergies between effects are not taken into account. Furthermore, indirect effects are not considered. Each sector is treated in a partial analysis. Scheraga *et al.* (1993) is one of the few exceptions.

The following section surveys these studies in more detail. Compared to the Second Assessment Report of the IPCC (Pearce *et al.*, 1996), the initial results are further corrected for purchasing power parity exchange rates and a typographical error is restored. The remaining sections then analyze how the assessments might change in the light of recent findings, and outlines further developments under way to improve on the current generation of estimates.

2. Results from Equilibrium Analysis

The scientific research on global warming impacts has focused predominantly on the potential climate change associated with the (arbitrarily chosen) $2 \times CO_2$ scenario, i.e., the impacts of an atmospheric CO_2 concentration of twice the preindustrial level. In addition, most research focuses on the impact climate change would have on the present situation. Although counterfactual, this has the advantages that only one variable (climate) is varied, and that projections of future worlds are avoided. Most of the figures reported below are based on these two prerequisites.

Climate change impacts can be classified as either market related or non-market related (impacts affecting 'intangibles' such as ecosystems or human amenity). Table I categorises the expected impacts from global warming. It also assesses how carefully they have been estimated in the literature so far.

Monetary estimates of both market and non-market damages can be expressed in the form of willingness to pay to obtain a good or service (WTP), or willingness to accept compensation to forego a good or service (WTA). Roughly, WTP measures the amount of income a person is willing to forego in exchange for an improved state of the world, and WTA is an estimate of the compensation required in order to accept a deterioration. With regard to climate change, WTP values improvements relative to baseline climate change, while WTA values deteriorations from the present. In practical applications, the two measures are often used interchangeably, despite the fact that WTA estimates are generally higher than WTP, and sometimes substantially so. Studies on climate change damage costs predominantly focuses on WTP, although WTA has also been used for some damage categories (e.g., mortality risks). Unfortunately, WTP/WTA estimates are not available for all global warming impacts. Reductions in revenues, the return on input factors (such as capital or land), and other indicators are frequently used to approximate the welfare impacts of climate change (see Table I). Often, WTP/WTA estimates are based on the transfer of results from issues other than climate change, or from one region to another.

It is clear from Table I that despite a growing body of literature much remains to be done. Available estimates on the costs of climate change are neither accurate nor complete. There is a considerable range of error. Figures on developing countries in particular are usually based on approximation and extrapolation, and are clearly

Table I. Overview on climate change impacts

Damages	*Market Impacts*				*Non-Market Impacts*		
	Primary economic sector damage	Other economic sector damage	Property loss	Damage from extreme events	*Ecosystem damage*	*Human impacts*	*Damage from extreme events*
Fully estimated based on willingness to pay	agriculture		dryland loss coastal protect.		wetland loss		
Fully estimated, using approximations	forestry	water supply		hurricane damage	forest loss		hurricane damage
Partially estimated	fisheries[1] leisure activity	energy demand infrastructure	urban droughts[2]	damage from	species loss air pollution	human life droughts[2] water pollution migration	damage from
Not estimated		insurance construction transport energy supply		non trop. storms river floods hot/cold spells other catastrophes	other ecosystems loss	morbidity physical comfort polit. stability *human hardship*	non trop. storms river floods hot/cold spells *other catastrophes*

[1] Often included in wetland loss.
[2] Primarily agricultural damage.
Sources: Pearce *et al.* (1996).

less reliable than those for developed regions. Nevertheless, the available estimates can serve as an indication of the relative vulnerability of different regions.

Climate change will affect a broad range of economic sectors and activities, as well as natural systems (cf. Table I). Table II shows the relative importance of different damage categories, using figures for the United States. As mentioned, the US is the country with the best available data to date. Impacts on coastal zones, human health, water supply and agricultural production are likely to be among the most serious effects. Note that estimates include both adaptation costs and residual damages. The former include the costs of coastal protection, the costs of migration, and the change in energy demand due to alterations in space heating and cooling requirements. The underlying adaptation assumptions, however, are not explicitly stated for most impact categories. Table III, which is based on the literature survey of IPCC Working Group III (Pearce *et al.*, 1996), shows the aggregate damages typically associated with $2 \times CO_2$. Figures vary between 0 and 9 percent of GDP, with damages in developing countries typically higher than those in OECD countries. The estimates reported by IPCC, while in most cases corrected for differences in purchasing power parity (PPP), are expressed as a percentage of uncorrected GDP. In addition to these figures, Table III also shows own calculations in which a PPP correction was made whenever this had not been done initially. These latter estimates are expressed as a percentage of real (PPP-corrected) GDP. The difference between the two sets of estimates is small compared to the likely range of error.

Considerable regional differences are likely, with potentially higher impacts for some individual countries, such as small island states. Table IV shows some of the estimates underlying the PPP estimates of Table III, highlighting the substantial differences between regions (for details on the original estimates, cf. Pearce *et al.*, 1996). For the former Soviet Union, PPP corrected damage could be as low as 0.4 percent of real (PPP-corrected) GDP, or even negative (climate change is potentially beneficial). Asia and Africa, on the other hand, could face extremely high damages, mainly due to the severe life/morbidity impacts. Estimates of the costs of mortality are extremely volatile and controversial, however, and should be interpreted with caution (cf. the discussion in Pearce *et al.*, 1996). Developing countries generally tend to be more vulnerable to climate change than developed countries, because of the greater importance of agriculture, lower health standards and the stricter financial, institutional, and knowledge constraints on adaptation.
The global estimates in Table III result from the aggregation of regional figures. The damage costs of each region are simply added up. This process has sometimes been criticised for not giving enough prominence to damages in developing countries. To incorporate equity considerations, one could make adjustments in the aggregation procedure. Fankhauser *et al.* (1996b) explore the issue of 'equity weights' in detail.

The figures in Tables II to IV are *best guess* estimates – the ranges does not reflect the uncertainties. Explicit uncertainty assessments are rare and far from comprehensive (see Morgan and Keith, 1995; Nordhaus, 1994b; Parry, 1993; Tol,

Table II. Economic damages from $2 \times CO_2$: Present US economy (base year 1990; billion \$)

	$2 \times CO_2$				
	Cline (2.5°C)	Fankhauser (2.5°C)[1]	Nordhaus (3°C)[1]	Titus (4°C)	Tol (2.5°C)[2]
Agriculture	17.5	8.4	1.1	1.2	10.0
Forest loss	3.3	0.7	small	43.6	—
Species loss	$4.0 + a^3$	8.4	[4]	—	5.0
Sea level rise	7.0	9.0	12.2	5.7	8.5
Electricity	11.2	7.9	1.1	5.6	—
Non-el. heating	−1.3	8.4	1.1	1.2	10.0
Human amenity	$+b^3$	—		—	12.0
Human morbidity	$+c^3$	—		—	—
Human life	5.8	11.4		9.4	37.4
Migration	0.5	0.6		—	1.0
Hurricanes	0.8	0.2		—	0.3
Construction	$\pm d^3$	—	[4]	—	—
Leisure activities	1.7	—		—	—
Water supply					
availability	7.0	15.6		11.4	—
pollution	—	—		32.6	—
Urban infrastruc.	0.1	—		—	—
Air pollution		7.3			—
tropos. ozone	3.5			27.2	
other	$+e^3$			—	
Mobile air cond.	—	—		2.5	—
Total	61.1 $+a+b+c\pm d+e$	69.5	55.5	139.2	74.2
(% pf GDP)	61.1	(1.3)	(1.0)	(2.5)	(1.5)[2]

[1]Transformed to 1990 base.
[2]USA and Canada, base year 1988.
[3]Identified, but not estimated.
[4]Not assessed categories, estimated at 0.75% of GDP.
Sources: Cline (1992a); Fankhauser (1995a); Nordhaus (1991); Titus (1992); Tol (1995).

1995). They neglect the possibility of impact surprises, and of low probability/high impact events (such as a shut down of the Gulf Stream). As mentioned, figures have been derived by imposing $2 \times CO_2$ onto a society with today's structure. The long-term vulnerability profile could change as a consequence of economic development and population growth. The advantages of using today's society are that only one variable (climate) is changed at the time, and that projections of future societies are avoided (see Tol, 1996, and Fankhauser and Tol, 1996, for further discussion).

Table III. Aggregate monetary damage for 2 × CO_2 (Annual damages)

Region	Damage Original IPCC estimate (% of GDP)	Full PPP correction (% of real GDP[1])
Developed countries (OECD)	1–2%	1–4%
Developing countries and Countries with economies in Transition	2–9%	0–7%
World	1.5–2%	1–2%

GDP corrected for differences in purchasing power parity.
Source: Pearce *et al.* (1996) and own calculations.

Table IV. Monetary 2 × CO_2 damage in different world regions and share of tangible damage (PPP-corrected annual damages)

	Fankhauser bn$	%rGDP[1]	tangible[2] (%)	Tol bn$	%rGDP[1]	tangible[2] (%)
• European Union	63.6	1.4	0.58			
• United States	61.0	1.3	0.61			
• Other OECD	55.9	1.2	0.59			
• OECD America				74.5	1.5	0.25
• OECD Europe				57.4	1.6	0.05
• OECD Pacific				60.7	3.8	0.09
Total OECD	180.5	1.3	0.59	192.7	1.9	0.14
• E. Europe/Former USSR	29.8[3]	0.4[3]	0.83[3]	−14.8	−0.4	2.37
• Centrally Planned Asia	50.7[4]	2.9[4]	0.90[4]	−4.0	−0.1	5.46
• South and South East Asia				92.2	5.3	0.74
• Africa				46.4	6.9	0.78
• Latin America				40.3	3.1	0.65
• Middle East				11.5	5.5	0.39
• Total non-OECD	141.6	0.9	0.77	171.8	1.7	0.46
World	322.0	1.1	0.67	364.4	1.8	0.29

[1]PPP-corrected GDP.
[2]Share of market in total damage.
[3]Former USSR only.
[4]China only.
Source: Own calculations based on Pearce *et al.*, 1996.

The relatively wide range of results shows that, although a rough picture on regional vulnerability to climate change is starting to emerge, much further research is necessary to improve the currently limited understanding of the issue.

3. New Findings in Equilibrium Analysis

The scientific understanding of climate change and climate change impacts is increasing rapidly. Socio- economic analysis that is based on these scientific findings tends to lag behind scientific progress. Most of the studies surveyed in the previous sections work with the climate and impact scenarios of the 1990 and 1992 IPCC reports (Houghton *et al.*, 1990, 1992). New findings and methodological advancements that have taken place since then only now start to trickle down into socio-economic analysis. Important recent developments include:

(a) *Increased emphasis on adaptation*: The important role of adaptation in climate change impact assessment has been increasingly recognised, and particularly in agricultural impact work, individual and societal responses to a changing climate are now regularly included in the analysis. As it turns out, model results are quite sensitive to assumptions on adaptability. Comparisons of model results with and without adaptation suggest that low-cost adaptation measures may reduce agricultural damages by about 30–60%, or even change the sign (Reilly *et al.*, 1996; Darwin *et al.*, 1995).

(b) *Increased emphasis on variability and extreme events*: While many of the earlier studies focused on changes in the mean (mostly global mean temperature) increasing attention is being paid to the variability around that mean, changes in which e.g. dominate the impact on agriculture (Mearns, 1995; Mearns *et al.*, 1996a,b), and to weather extremes. Extremes, such as floods, droughts, heat waves, and storms, do not only determine a large share of the damage, they also drive adaptation (Downing *et al.*, 1996).

(c) *Increased emphasis on non-climate change related stress factors*: In many cases, climate change will add to already existing stress on natural ecosystems. Examples of such multiple stress situations include the development of coastal zones, water use, and land use change. The existence of multiple stress factors could seriously compound ecosystem impacts (Watson *et al.*, 1996). By implication, measures that tackle current environmental problems would seem to be a low-cost, or even 'no-regret' strategy to strengthen the resilience of ecosystems. A similar argument could also hold with respect to imperfections affecting the performance of the economic system, such as restrictions in the trade of agricultural goods, or insufficient nutritional and health standards.

(d) *Importance of integrated assessment*: There are strong inter-linkages between the different sectors impacted by climate change, as well as between impacted sectors and those not directly affected by climate change. For example, agricultural, forest and ecosystem impacts are linked through land use competition; the scope for irrigation as an adaptive measure in the agricultural sector depends on the impacts felt in the water sector, and so on. In addition, there may be repercussions between impacts and possible mitigation policies, e.g. in the forestry, agriculture and energy sectors. To capture these effects climate change studies have increasingly made use of integrated assessment models (see Weyant *et al.*, 1996, for a survey). This also ensures consistency between the underlying assumptions.

How do these and other scientific developments affect the damage assessment of the previous sections? Three broad tendencies seem to emerge.

Trend 1: Increasing Regional and Sectoral Differences
Recent findings stress the regional diversity of impacts. The notion that a warmer world will know winners as well as losers now features far more prominently than in the first generation of assessments. A recent study for Finland, for instance, finds this country to be a net winner from climate change (Kuoppomaeki, 1996). Agricultural studies such as Rosenzweig and Parry (1994), Reilly *et al.* (1994) or Darwin *et al.* (1995) identify many developed and other northern latitude countries as possible winners, provided farmers take adequate adaptation measures. Food insecurity in the South, on the other hand, is likely to be further aggravated.

Differences are also increasingly emphasised between different regions within a country, and between different agents, sectors and commodities. A US forestry study by Callaway *et al.* (1994) is a good example. It estimates annual losses in US welfare ($2.5–6.5 m/yr for 2.5°C warming) that are comparable to e.g. Cline's (1992a) initial estimate ($3.3 m), but with significant differences for individual regions and products. For example, softwood yields are expected to decrease, except in the North West, while yields in hardwood would mostly increase, except perhaps in the South. Producers could significantly gain as a consequence of higher prices, while consumer surplus is expected to drop (Callaway *et al.*, 1994).

Trend 2: Lower Market Impacts in Developed Countries
Re-assessments of market-related impacts in developed countries have in many cases lead to a reduction in expected impacts compared to earlier estimates. Yohe *et al.* (1996), for example, observe a continuous decrease in estimated damage costs from sea level rise. Calculations for the US by Rosenthal *et al.* (1995) suggest that earlier estimates of energy sector costs may have been too high, and that climate change may in fact be beneficial for the energy sector in many US regions. More recent agricultural estimates also tend to be lower than earlier assessments (Darwin *et al.*, 1995; Mendelsohn *et al.*, 1995; Adams *et al.*, 1994).

Adjustments in estimates have occurred for a variety of reasons. In the case of sea level rise, much of the downscaling occurred as a result of discounting effects and more modest rise scenarios. One of the reasons for lower damages in the Adams *et al.* (1994) study is their extension of the model to include more heat tolerant crops such as fruits and vegetables. In many cases, however, lower estimates are predominantly the result of better incorporation of the effects of adaptation.

Whether this trend to decreasing estimates of market impacts can be extended from industrialised countries to other regions is not clear. The answer depends on the exact reasons that have led to a reassessment. Reductions associated with adaptation effects, for example, will not extend to other regions as easily as, say, the effect of a lower sea level rise projection. It is generally assumed that developing countries will lack the financial, institutional and technical capacity to efficiently adapt to a warmer world in the same way as industrialised countries will (Reilly *et al.*, 1996; in fact, this is one of the reasons why regional variability of damages is higher in recent studies). Estimates of market impacts on developing countries (given their current situation) may therefore fall to a lesser extent.

Trend 3: Increasing Importance of Non-Market Impacts

While estimates of market impacts are often corrected downwards, new results on non-market impacts suggest that these effects may initially have been underestimated. Improvements in this area have not so much occurred with respect to the accuracy of figures – it remains low – than with respect to their comprehensiveness. Some non-market impacts that were neglected in earlier analysis for lack of data can now be quantified. This is most notably the case for health impacts, where numerical estimates are now available for the expected spread of malaria in a warmer world. Integrated modelling work by Matsuoka and Kai (1995) suggests a 10–30% increase in areas with potential malaria risk, while Martens *et al.* (1994) expect several million additional malaria cases by the year 2100. Recent speculation about a link between climate change and the spread of diseases such as cholera and dengue fever suggest that the health impacts of climate change may have been underestimated so far (McMicheal *et al.*, 1996). In addition, the risk of hunger (Rosenzweig and Parry, 1994) and migration (Myers and Kent, 1995) have gained more analytical attention.

Since the finalization of the IPCC Second Assessment Report, one new comprehensive study of the damage costs of climate change has emerged, of which drafts are currently circulated (Mendelsohn *et al.*, 1996a,b). Although the study does not deal with all of the above developments and trends, it is sometimes referred to as a 'new generation of damage estimation'. Adaptation is brought prominently to the fore (consequently,market impacts in developing countries are estimated lower than in earlier assessments), but most of the other points are neglected. While the importance of non-market impacts is acknowledged, the study by and large concentrates on tangible damages. Attention focuses on the opportunity costs of a different climate. Transition effects and the process of adaptation are ignored. Novel is the presentation of damages as a *function* of temperature as well as *precipitation*. Earlier studies had merely analysed damage for a benchmark temperature change. As with earlier studies, the USA is again studied in detail while damages for the rest of the world are derived by extrapolation.

Table V. Market impacts (per cent of GDP), 2.5°C warming[1]

Region	Fankhauser	Mendelsohn *et al.*	Tol
OECD	0.77	−0.17	0.27
non-OECD	0.67	0.03	0.76
'North'[2]	0.60	−0.23	−0.06
'South'[2]	1.02	0.17	1.66
World	0.72	−0.08	0.52

[1]Mendelsohn *et al.* assume a 2.5°C rise in global mean temperature to take place in 2060, whereas Fankhauser and Tol assume this to happen in 2050. Note that only Tol has damage depending on the rate of climate change. In all three cases, vulnerability is assumed as in 1988/1990.
[2]The countries subsumed under the labels 'North' and 'South' differ between the assessments. Fankhauser's North is OECD plus former Soviet Union. Mendelsohn *et al.*'s North is North and Central America, Europe and Oceania for damages, and USA, other OECD and former Soviet Union for GDP. Tol's North is OECD plus Central and Eastern Europe and the former Soviet Union.
Sources: Fankhauser (1995a), Tol (1995), Mendelsohn *et al.* (1996a,b) and own calculations.

Table V compares the findings of Mendelsohn *et al.* (1996b) with those of Fankhauser (1995a) and Tol (1995) (for market damage only). The more recent study by Mendelsohn *et al.* is consistently more optimistic than the earlier work. This is because Mendelsohn *et al.* assume a greater adaptation potential than Fankhauser and Tol do, and often ignore the costs of adaptation. However, by extrapolating the adaptation potential of the US to other regions, Mendelsohn *et al.* probably overestimate the adaptive capacity of developing countries. Fankhauser and Tol in contrast use evidence from outside the USA where available. In terms of results, Fankhauser is most pessimistic for the OECD, the 'north' and the world, while Tol is most pessimistic about the non- OECD and the 'south'. The best guess of both Mendelsohn *et al.* and Tol is that the 'north' may gain from a modest climate change. Mendelsohn *et al.* come to the same conclusion for the OECD and the world.

4. Results from Dynamic Analysis

The analysis so far was confined to comparative statics. All figures in Tables II to V are estimates of the impact of one specific change of the climate ($2 \times CO_2$) on the current economy. This is clearly insufficient. Not only will we, for the larger part of the future, be confronted with climate change substantially different from $2 \times CO_2$, but socio- economic vulnerability to climate change could also shift as a consequence of economic development.

What would be relevant to know from a policy point of view are marginal figures, i.e., estimates of the extra damage done by one extra tonne of carbon emitted. Unfortunately, the requirements for marginal damage calculations go far beyond the information available from $2 \times CO_2$ studies. Greenhouse gases are stock pollutants. That is, fractions of the gas, once emitted, remain in the atmosphere for several decades, and consequently affect climate over this period of time. Calculating marginal costs therefore requires the comparison of two present value terms: The discounted sum of future damages associated with a certain emission scenario has to be compared to the discounted sum of damages in an alternative scenario with marginally different emissions in the base period. In estimates based on optimal control models (e.g., Nordhaus, 1994a; Peck and Teisberg, 1991, 1993) the marginal costs is calculated as the shadow price of carbon, i.e., the carbon tax necessary to keep emissions on the socially optimal trajectory.

The current generation of models deals with this challenge in a rather ad hoc manner, using very simplistic representations of the complex dynamic processes involved. In older studies damage costs were typically specified as a power (usually linear to cubic) function of global mean temperature, calibrated around the $2 \times CO_2$ estimates. Damage is usually fully reversible and typically assumed to grow with GDP. Only recently, studies have started to emerge which explicitly incorporate regionally diversified temperatures and sea levels, model individual damage categories (e.g., agriculture) separately, or at least distinguish between damages related to absolute temperature level and those related to the rate of change (Dowlatabadi and Morgan, 1993; Hope *et al.*, 1993; Tol, 1995, 1996). A first step towards a response function (rather than point estimates) of the opportunity costs of climate change was made by Mendelsohn *et al.* (1996a,b).

Table VI provides a list of estimates of the marginal damages obtained from polynomial damage models. Estimates range from about \$5 to \$125 per tonne of carbon, with most estimates at the lower end of this range. The wide range reflects variations in model assumptions, as well as the high sensitivity of figures to the choice of the discount rate (on discounting, cf. e.g. Arrow *et al.*, 1996). Estimates are expected to rise over time as a consequence of economic growth and increasing concentration levels.

Using his DICE model, Nordhaus (1994a) finds a shadow price starting at about \$5 per tonne of carbon in 1995, subsequently rising to about \$10 by 2025, and reaching \$21 by 2095 (at 1990 prices). Peck and Teisberg (1991, 1993) find values of a similar order of magnitude. Tol's (1994) alternative specification of DICE yields shadow prices of \$13 for 1995, rising to \$89 for 2095. These model runs all assume that parameter values are known with certainty. In the case of DICE, expected shadow prices more than double once uncertainty is added to the model. This result arises because of the skewedness in the damage distribution, which allows for low probability – high impact events (Nordhaus, 1994a). Risk aversion and concave damage functions further enhance this effect (Tol, 1995).

Table VI. The marginal social costs to the world of CO_2 emissions (current value (1990)$/tC

Study	Type[1]	1991–2000	2001–2010	2011–2020	2021–2030
Nordhaus	MC		7.3 (0.3–65.9)[2]		
Ayres and Walter	MC		30–35		
Nordhaus	CBA				
– best guess		5.3	6.8	8.6	10.0
– expected value		12.0	18.0	26.5	n.a.
Cline	CBA	5.8–124	7.6–154	9.8–186	11.8–221
Peck and Teisberg	CBA	10–12	12–14	14–18	18–22
Fankhauser[3]	MC	20.3 (6.2–45.2)[2]	22.8 (7.4–52.9)	25.3 (8.3–58.4)	27.8 (9.2–64.2)
Maddison	CBA/MC	5.9–6.1	8.1–8.4	11.1–11.5	14.7–15.2

[1]MC = marginal social cost study; CBA = shadow value in a cost-benefit study.
[2]Figures in brackets denote 90% confidence intervals.
[3]Fully corrected for PPP-exchange rates, Fankhauser's estimates would be about a factor 1.2 higher.
Sources: Pearce *et al.* (1996); see alsl Ayres and Walter (1991); Nordhaus (1991, 1994); Cline (1992b, 1993); Fankhauser (1994a); Peck and Teisberg (1991, 1993); Maddison (1994).

The studies mentioned above all assume a pure rate of time preference (or utility discount rate) of 3%. In contrast, Cline (1992b, 1993)* finds significantly higher shadow prices by using a zero utility discount rate. His reproduction of the DICE model generates a path of shadow prices beginning at about $45 per tonne, reaching about $243 by 2100. Other parameter specifications provide even higher values.

Fankhauser (1994a) identifies a lower and flatter trajectory for the shadow price of carbon, rising from $20 per tonne by 1991–2000 to $28 per tonne by 2021–2030, with confidence intervals of $6–45 and $9–64, respectively. Fankhauser uses a probabilistic approach to the range of discount rates, in which low and high discount rates are given different weights. His sensitivity analysis with the discount rate suggest that moving from high (3%) to low (0%) discounting could increase marginal costs by about a factor 9, from $5.5 to $49 per tonne of carbon emitted now.

As noted, most of the above studies model damage as a function of the *level* of climate change only. Arguably, the *rate* of climate change may be equally, and

* Cline, W.R.: 1992b, *Optimal Carbon Emissions over Time: Experiments with the Nordhaus DICE Model* (draft).
Cline, W.R.: 1993, *Modeling Economically Efficient Abatement of Greenhouse Gases* (draft).

perhaps even more important than the absolute level of change. Similarly, the costs of adaptation may be as important as the opportunity costs of foregone welfare. These issues have been little studied so far (cf. Fankhauser and Tol, 1996; Tol, 1996), even though the importance of adaptation is now well-recognized.

Successful adaptation depends on a variety of factors, all of which are difficult to model. It requires first of all a recognition of the necessity to adapt, and, following this recognition, knowledge about available options, the capacity to assess them and the ability to implement the most suitable ones. Recognition of the need to adapt in turn is fostered through awareness building measures (including research and dissemination) but also arises from experience. The insurance industry is a good example. The series of violent storms and floods since the late 1980s has made insurers aware of their exposure to weather hazards. A number of adaptation measures have already been implemented as a consequence, and more are being studied and discussed (cf. Downing *et al.*, 1996). The ability to identify, assess and implement adaptation options is hampered by the prevailing uncertainties. Without a clear picture of future climate, adaptation will initially be limited to options that make the system under consideration more flexible or more robust to weather variations. An exception are cases such as sea level rise, where the direction of change is known, although the magnitude and timing are not. Current adaptation measures will also be restricted to investments with a sufficiently long lifetime to witness substantial climate change (such as buildings, waterworks, natural reserves). For systems with a more rapid turnover time (e.g., agricultural practice) current measures will probably focus on building appropriate institutions and knowledge infrastructure (including medium-term climate forecasts and their dissemination to stakeholders).

Changes in socio-economic vulnerability are similarly important. Vulnerability to climate change will change through exogenous factors as well as through dedicated adaptation measures. The rough pattern of such change can be deduced from Table VI: Poorer regions appear to be more vulnerable to climate change than richer ones, presumably, as noted above, because they face stricter constraints on technology, capital and institutions. In addition, poorer countries tend to have a greater share of their economy in weather-sensitive sectors, in particular agriculture. Table VI also shows that the share of tangible impacts on total damage is greater in poorer regions, which again reflects the importance of weather-sensitive sectors and the relatively low valuation of intangible impacts. Hence, with growing affluence, tangible damages can be expected to fall (relative to income). Intangible damage on the other hand may rise, because of the impact of per capita income on valuation (see Fankhauser and Tol, 1996; Tol, 1996). Health damages may be an exception from this rough rule of thumb, as one would expect health care standards to improve with increasing affluence and this may offset the rise in valuation due to higher income. On the other hand, most impact studies conducted so far have neglected possible increases in tropical diseases as well as differences in health care between countries. That is, impact studies may have underestimated intangible damages.

In addition to affluence, other aspects of global change (e.g., globalization, soil erosion, deforestation, urbanisation, pollution) may also affect vulnerability to climate change, and this in either direction. It is generally accepted that systems which are already under great stress (e.g., agriculture suffering from soil erosion; people suffering under urban air pollution) will be more vulnerable to climate change. Ironically, if exogenous stress is too high, this may also diminish impacts, however, in the sense that ecosystems may be damaged beyond repair before climate change sets in. Coral reefs may be an example. Other processes, particularly economic globalization, could also reduce vulnerability by interconnecting markets, capital flows, and technology. To date, very little is known about these processes and their interrelationships with vulnerability to climate change.

5. Conclusion

In this paper we assess trends leading from the current state of the art of damage estimates, as reflected in the IPCC Second Assessment Report, to a new generation of improved estimates. Earlier studies estimate an aggregated monetised damage in the order of 1.5 to 2.0The OECD face damages equivalent to 1.0 to 1.5 % of GDP. Damage in developing countries would amount to 2.0 to 9.0 % of GDP. These figures are not comprehensive and highly uncertain. Ongoing research continues to update and extend the estimates, but formal assessments of uncertainty remain rare.

Newer studies increasingly emphasise the power of adaptation, the importance of weather variability and extreme events, the influence of other stress factors than climate change, and the need for integrated assessment of damages. The incorporation of these effects has resulted in more pronounced differences in estimates between different regions and sectors. Estimates of market damages in developed countries have tended to fall, while non-market impacts have become increasingly important.

Marginal damages and damage profiles are more interesting from a policy point of view. Earlier estimates of the marginal range from about $5 to $125 per tonne of carbon, with most estimates at the lower end of this range. These figures are based on polynomial damage functions with only one parameter: the level of climate change. Arguably, the rate of change may be equally important, though, as are the speed of adaptation, damage restoration and value adjustment. Unfortunately, little explicit attention has been paid to these matters thus far. In addition, future vulnerability to climate change may differ from current vulnerability. A common assumption is that market damages may grow at a lower rate than GDP, while non-market damages could grow at a higher rate. Mortality and morbidity losses may be an exception from this rule. For health related impacts one would expect the absolute number of casualties to fall over time, as medical standards improve, while at the same time the value people assign to a lower mortality risk may rise as per capita income grows.

In sum, the first generation of estimates of the damage costs of climate change is being substantially updated, extended and complemented, without, as yet, invalidating the earlier results. Among the most crucial research topics for the next period are:

(a) Impact on developing countries (cf. Section 1);
(b) Assessment and valuation of non-market losses, particularly human morbidity, unmanaged ecosystems, and irreversibilities (cf. Section 2);
(c) Weather variability and extreme weather events (cf. Section 4);
(d) Adaptation and adaptation policies (cf. Section 4);
(e) Vulnerability changes and vulnerability mitigation (cf. Section 5);
(f) Interlinkages between effects (cf. Section 1);
(g) Indirect effects on economy and environment (cf. Section 1);
(h) Uncertainty assessments and analyses (cf. Section 2);
(i) Equity and responsibility aspects of impact valuation, comparison and aggregation (cf. Section 3); and
(j) Communication and consistency between climatology, primary impact research and economic valuation (cf. Section 4).

The length of this research agenda is suggestive of the still rudimentary stage of the impact assessment of climate change. A major research effort will be required between now and the Third Assessment Report of the IPCC.

References

Adams, R.M., McCarl, B.A., Segerson, K., Rosenzweig, C., Bryant, K.J., Dixon, B.L., Conner, R., Evenson, R.E. and Ojima, D.: 1994, *The Economic Effects of Climate Change on US Agriculture*, Report prepared for the Electric Power Research Institute, Palo Alto, CA.

Arrow, K.J., Cline, W.R., Maler, K.-G., Munasinghe, M. and Stiglitz, J.E.: 1996, 'Intertemporal Equity, Discounting, and Economic Efficiency', in Bruce, J.P., Lee, H. and Haites, E.F. (eds.) *Climate Change 1995: Economic and Social Dimensions – Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

Asian Development Bank: 1992, *Climate Change in Asia*, 8 Country Studies, Manila: ADB.

Ayres, R.U. and Walter, J.: 1991, 'The Greenhouse Effect: Damages, Costs and Abatement', *Environmental and Resource Economics* **1**, 237–270.

Bijlsma, L., Ehler, C.N., Klein, R.J.T., Kulshrestha, S.M., McLean, R.F., Mimura, N., Nicholls, R.J., Nurse, L.A., Perez Nieto, H., Stakhiv, E.Z., Turner, R.K. and Warrick, R.A.: 1996, 'Coastal Zones and Small Islands', in Watson, R.T., Zinyowera, M.C. and Moss, R.H. (eds.) *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses – Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

Callaway, J., Smith, J.B. and Keefe, S.: 1994, *The Economic Effects of Climate Change for US Forests*, RCG/Hagler Bailly, Boulder.

Cline, W.R.: 1992a, *The Economics of Global Warming*, Institute for International Economics, Washington, D.C.
CRU/ERL: 1992, *Development of a Framework for the Evaluation of Policy Options to Deal with the Greenhouse Effect: Economic Evaluation of Impacts and Adaptive Measures in the European Community*, University of East Anglia, Norwich.
Darwin, R., Tsigas, M., Lewandrowski, J. and Raneses, A.: 1995, *World Agriculture and Climate Change – Economic Adaptations*, Agricultural Economic Report **703**, U.S. Department of Agriculture, Washington, D.C.
Dixon, R.K., Guill, S., Mkanda, F.X. and Hlohowskyj, I.: 1996, *Climate Research Special: Vulnerability and Adaptation of African Ecosystems to Global Climate Change*, Inter-Research, Oldendorf/Luhe.
Dowlatabadi, H. and Morgan, G.: 1993, 'A Model Framework for Integrated Studies of the Climate Problem', *Energy Policy*, 209–221.
Downing, T.E., Olsthoorn, A.A., and Tol, R.S.J.: 1996, *Climate Change and Extreme Events – Altered Risk, Socio-economic Impacts and Policy Responses*, Institute for Environmental Studies, Vrije Universiteit and Environmental Change Unit, University of Oxford, Amsterdam and Oxford.
Fankhauser, S.: 1994a, 'The Social Costs of Greenhouse Gas Emissions: An Expected Value Approach', *The Energy Journal* **15**(2), 157–184.
Fankhauser, S.: 1994b, 'The Economic Costs of Global Warming Damage: A Survey', *Global Environmental Change* **4**(4), 301–309.
Fankhauser, S.: 1995a, *Valuing Climate Change – The Economics of the Greenhouse*, EarthScan, London.
Fankhauser, S.: 1995b, 'Protection vs. Retreat – The Economic Costs of Sea Level Rise', *Environment and Planning A* **27**, 299–319.
Fankhauser, S., Tol, R.S.J. and Pearce, D.W.: 1996a, *Extensions and Alternatives to Climate Change Damage Valuation: On the Critique of IPCC Working Group III's Damage Estimates*, Working Paper, Centre for Social and Economic Research on the Global Environment, University College London and University of East Anglia, forthcoming.
Fankhauser, S., Tol, R.S.J. and Pearce, D.W.: 1996b, *Equity and the Aggregation of Climate Change Damages*, Working Paper, Centre for Social and Economic Research on the Global Environment, University College London and University of East Anglia, forthcoming.
Fankhauser, S. and Tol, R.S.J.: 1996, 'Recent Advancements in the Assessment of the Damage Costs of Climate Change', *Energy Policy* **24**(7), 665–673.
Hope, C.W., Anderson, J. and Wenman, P.: 1993, 'Policy Analysis of the Greenhouse Effect – An Application of the PAGE Model', *Energy Policy* **15**, 328–338.
Houghton, J.T., Callander, B.A., and Varney, S.K.: 1992, *Climate Change 1992 – The Supplementary Report of the IPCC Scientific Assessment*, Cambridge University Press, Cambridge.
Houghton, J.T., Jenkins, G.J. and Ephraums, J.J.: 1990a, *Climate Change – The IPCC Scientific Assessment*, Cambridge University Press, Cambridge.
Kuoppamaki, P.: 1996, *Impacts of Climate Change from a Small Nordic Open Economy Perspective – The Potential Impacts of Climate Change on the Finnish Economy*, ETLA, Helsinki.
Lenhart, S., Huq, S., Mata, L.J., Nemesova, I., Toure, S. and Smith, J.B. (eds.): 1996, *Vulnerability and Adaptation to Climate Change – A Synthesis of Results from the U.S. Country Studies Program*, Interim Report January 1996 U.S. Country Studies Program, Washington, D.C.
Maddison, D.: 1994, *The Shadow Price of Greenhouse Gases and Aerosols*, draft, Centre for Social and Economic Research on the Global Environment, London and Norwich.
Martens, W.J.M., Rotmans, J. and Niessen, L.W.: 1994, *Climate Change and Malaria Risk: An Integrated Modelling Approach*, RIVM, Bilthoven.
Matsuoka, Y. and Kai, K.: 1995, 'An Estimation of Climatic Change Effects on Malaria', *Journal of Global Environment Engineering* **1**, 43–58.
McMicheal, A.J., Ando, M., Carcavallo, R., Epstein, P., Haines, A., Jendritzky, G., Kalkstein, L., Odongo, R., Patz, J. and Piver, W.: 1996, 'Human Population Health', in Watson, R.T., Zinyowera, M.C. and Moss, R.H. (eds.) *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses – Contribution of Working Group II to the Second*

Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

Mearns, L.O.: 1995, 'Methodological Issues Concerning the Determination of the Effects of Change in Climatic Variability on Crop Yields', in Rosenzweig, C. (ed.) *Climate Change and International Impacts*, American Society of Agronomy, Madison.

Mearns, L.O., Rosenzweig, C. and Goldberg, R.: 1996a, 'The Effects of Changes in Daily and Interannual Climatic Variability on CERES-Wheat: A Sensitivity Study', *Climatic Change* **32**, 257–292.

Mearns, L.O., Rosenzweig, C. and Goldberg, R.: 1996b, *Mean and Variance Change in Climate Scenarios: Methods and Agricultural Applications* (draft).

Mendelsohn, R., Nordhaus, W.D. and Shaw, D.: 1995, 'The Impact of Climate on Agriculture: A Ricardian Analysis', *American Economic Review* **84**(4), 753–771.

Mendelsohn, R., Adams, R., Callaway, J.M., Hurd, B., McCarl, B., Morrison, W., Segerson, K., Smith, J., Sohngen, B. and Yohe, G.: 1996a, *The Market Impacts of Climate Change in the US* (draft).

Mendelsohn, R., Morrison, W., Schlesinger, M.E. and Andronova, N.G.: 1996b, *A Global Impact Model for Climate Change* (draft).

Morgan, M.G. and Keith, D.W.: 1995, 'Subjective Judgments by Climate Experts', *Environmental Science and Technology* **29**(10), 468A–476A.

Myers, N. and Kent, J.: 1995, *Environmental Exodus – An Emergent Crisis in the Global Arena*, Climate Institute, Washington, D.C.

Nishioka, S., Harasawa, H., Hashimoto, H., Ookita, T., Masuda, K. and Morita, T.: 1995, *The Potential Effects of Climate Change in Japan* I009–'93, Center for Global Environmental Research, Tsukuba.

Nordhaus, W.D.: 1991, 'To Slow or Not to Slow: The Economics of the Greenhouse Effect', *Economic Journal* **101**, 920–937.

Nordhaus, W.D.: 1994a, *Managing the Global Commons: The Economics of Climate Change*, The MIT Press, Cambridge.

Nordhaus, W.D.: 1994b, 'Expert Opinion on Climate Change' *American Scientist*, Jan/Feb, 45–51.

Parry, I.W.H.: 1993, 'Some Estimates of the Insurance Value against Climate Change from Reducing Greenhouse Gas Emissions, *Resource and Energy Economics* **15**(1), 99–116.

Parry, M.L. and Duncan, R.: 1995, *The Economic Implications of Climate Change in Britain*, Earthscan, London.

Pearce, D.W., Cline, W.R., Achanta, A.N., Fankhauser, S., Pachauri, R.K., Tol, R.S.J. and Vellinga, P.: 1996, 'The Social Costs of Climate Change: Greenhouse Damage and the Benefits of Control', in Bruce, J.P., Lee, H. and Haites, E.F. (eds.) *Climate Change 1995: Economic and Social Dimensions – Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

Peck, S.C. and Teisberg, T.J.: 1991, 'CETA: A Model for Carbon Emissions Trajectory Assessment', *The Energy Journal* **13**(1), 55–77.

Peck, S.C. and Teisberg, T.J.: 1993, 'Global Warming Uncertainties and the Value of Information: An Analysis using CETA', *Resource and Energy Economics* **15**, 71–97.

Reilly, J.: 1996, *Climate Change, Global Agriculture, and Regional Vulnerability* (draft).

Reilly, J., Baethgen, W., Chege, F.E., van de Geijn, S.C., Lin, E., Iglesias, A., Kenny, G., Patterson, D., Rogasik, J., Roetter, R., Rosenzweig, C., Sombroek, W. and Westbrook, J.: 1996, 'Agriculture in a Changing Climate: Impacts and Adaptation', in Watson, R.T., Zinyowera, M.C. and Moss, R.H. (eds.) *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses – Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

Reilly, J.M., Hohmann, N. and Kane, S.: 1994, 'Climate Change and Agricultural Trade: Who Benefits, Who Loses?', *Global Environmental Change* **4**(1), 24–36.

Rosenthal, D.H., Gruenspecht, H.K. and Moran, E.A.: 1995, 'Effects of Global Warming on Energy Use for Space Heating and Cooling in the United States', *Energy Journal* **16**(2), 77–98.

Rosenzweig, C. and Parry, M.L.: 1994, 'Potential Impact of Climate Change on World Food Supply', *Nature* **367**, 133–138.

SAARC: 1992, *Regional Study of the Greenhouse Effect and its Impact on the Region*, South Asian Association for Regional Cooperation, Kathmandu.

Scheraga, J.D., Leary, N.A., Goettle, R.J., Jorgenson, D.W. and Wilcoxen, P.J.: 1993, 'Macroeconomic Modeling and the Assessment of Climate Change Impacts', in Kaya, Y., Nakicenovic, N., Nordhaus, W.D. and Toth, F. (eds.) *Costs, Impacts and Benefits of CO_2 Mitigation*, CP-93-2, International Institute for Applied Systems Analysis, Laxenburg.

Smith, J.B., Bhatti, N., Menzhulin, G., Bemoff, R., Budyko, M.I., Campos, M., Jallow, B., Rÿsberman, F. and Dixon, R.K.: 1997, *Adapting to Climate Change: Assessments Issues*, Springer, Berlin.

Smith, J.B. and Tirpak, D.A. (eds.): 1989, *The Potential Effects of Global Climate Change on the United States*, US Enviromental Protection Agency, Washington, D.C.

Strzepek, K.M. and Smith, J.B.: 1995, *As Climate Changes – International Impacts and Implications*, Cambridge University Press, Cambridge.

Tegart, W.J.M., Sheldon, G.W., and Griffiths, D.C.: 1990, *Climate Change – The IPCC Impacts Assessment*, Australian Government Publishing Service, Canberra.

Tegart, W.J.M., Sheldon, G.W., and Hellyer, J.H.: 1992, *Climate Change 1992 – The Supplementary Report to the IPCC Impacts Assessment*, Australian Government Publishing Service, Canberra.

Titus, J.G.: 1992, 'The Costs of Climate Change to the United States', in Majumdar, S.K., Kalkstein, L.S., Yarnal, B., Miller, E.W. and Rosenfeld, L.M. (eds.) *Global Climate Change: Implications, Challenges and Mitigation Measures*, Pennsylvania Academy of Science.

Tol, R.S.J.: 1994, 'The Damage Costs of Climate Change – A Note on Tangibles and Intangibles, Applied to DICE', *Energy Policy* **22**(5), 436–438.

Tol, R.S.J.: 1995, 'The Damage Costs of Climate Change Toward More Comprehensive Calculations', *Environmental and Resource Economics* **5**, 353–374.

Tol, R.S.J. (1996), 'The Damage Costs of Climate Change Toward a Dynamic Representation', *Ecological Economics* **19**(1), 67–90.

Watson, R.T., Zinyowera, M.C., and Moss, R.H.: 1996b, *Climate Change 1995: Impacts, Adaptation, and Mitigation of Climate Change – Scientific-Technical Analysis – Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

Weyant, J., Davidson, O., Dowlatabadi, H., Edmonds, J., Grubb, M., Parson, T., Richels, R., Rotmans, J., Shukla, P., Tol, R.S.J., Cline, W.R. and Fankhauser, S.: 1996, 'Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results', in Bruce, J.P., Lee, H. and Haites, E.F. (eds.) *Climate Change 1995: Economic and Social Dimensions – Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

Yohe, G., Neumann, J. and Ameden, H.: 1995, 'Assessing the Economic Cost of Greenhouse-Induced Sea Level Rise: Methods and Applications in Support of a National Survey', *Journal of Environmental Economics and Management* **29**, S-78-S-97.

Yohe, G.W., Neumann, J.E., Marshall, P.B. and Ameden, H.: 1996, 'Wading Through the Greenhouse – The Shrinking Economic Cost of Greenhouse Induced Sea Level Rise in the United States', *Climatic Change* **32**, 387–410.